THE METEOROLOGICAL MAGAZINE

HER MAJESTY'S STATIONERY OFFICE

September 1986

Met.O.971 No. 1370 Vol. 115

METEOROLOGICAL OFFICE Met.O.971

THE METEOROLOGICAL MAGAZINE

No. 1370, September 1986, Vol. 115

551.551.5:551.509.5:629.7

Automated clear air turbulence forecasting

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Summary

A trial with three major civil airlines was held during 1984–5. Computer-produced forecast charts of clear air turbulence probability were issued to pilots of selected flights with a request for annotation of route and turbulence experienced on the flight. Over 700 charts were returned; a statistical analysis of these has demonstrated a significant degree of skill in the probability forecasts.

Introduction

Clear air turbulence (CAT) is responsible for discomfort and injury to airline passengers and crew, increased flying costs and, occasionally, stress damage to aircraft. Since there is, as yet, no on-board method of detecting CAT in advance of an encounter, any improvements in the forecasting of CAT of moderate or severe intensity must be welcomed by the civil airline operators and the military.

Computer forecasts of moderate or severe CAT for 18 and 24 hours ahead have been produced on a regular basis by the Meteorological Office since 1980. The algorithm in use was derived by Dutton (1980) using multiple regression techniques to correlate civil airline pilot reports obtained during the 1976 North Atlantic Turbulence Survey with forecast parameters from the operational numerical weather prediction (NWP) model. Details of the algorithm itself are given in Appendix 1.

Recognized deficiencies in the forecasts produced by the old 10-level NWP model, namely inaccuracies in the positions and strengths of jet streams, reduced the accuracy of the automated CAT forecasts, and their dissemination to customers was, therefore, not warranted. However, with the introduction of the new global 15-level model (which has a grid length of about 150 km in mid-latitudes) in September 1982, the forecasting of jet streams has improved sufficiently to consider operational use of these automated CAT forecasts.

A limited verification exercise was undertaken in the winter of 1982/83 and this demonstrated that the skill of the objective CAT forecast was significantly higher than that of the subjective forecast (which was used as input to the routine significant weather chart). This led to the arrangement of a trial with British Airways (BA) whereby the meteorological office at London/Heathrow provided a computer-generated chart of the forecast CAT probability for selected North Atlantic and European flights, with a request to the pilot to annotate the chart with the route, the turbulence experienced on the flight, any other relevant comments, and the return of the chart.

The trial, which began in July 1984 and lasted until the end of July 1985, served three main functions. Firstly, it introduced pilots to a new type of forecast, namely one in which the parameter being forecast was expressed in terms of a probability of occurrence. This is more difficult to comprehend and use than a conventional yes/no type of forecast. Secondly, it provided sufficient material to conduct a detailed verification exercise and thirdly, it provided the data to carry out statistical regressions in the future, if required, to improve the forecasts further.

Details of the trial

During the first 5 months of the trial, charts were issued to five BA flights daily — three North Atlantic (New York or Washington) and two European (Athens or Tel Aviv). As the number of charts returned was rather low (less than 10%), BA agreed to extend the trial to cover all long-haul flights departing from Heathrow, and also to invite Pan American World Airways (PA) and Air Canada (AC) to join in the trial. From December, charts were issued to about 100 BA flights per week. An additional chart covering Europe and much of Asia and Africa was produced and disseminated to BA flights to the Middle East, India and East Africa. From February, charts were also issued to three PA flights daily (two to New York, one to San Francisco), and from April to three AC flights daily (one to Toronto, the others to Edmonton, Calgary or Vancouver). The number of charts returned from PA was about 33%, and from AC about 40%. The return rate from BA increased only slightly to about 10%. In all 821 charts were returned over the 13-month trial period. However, some of these charts had no indication of the route flown and had to be discarded. Also charts from 2–9 February were not included because during this period the Meteorological Office Cyber computer was withdrawn from service (to allow enhancement work to be carried out), and Washington data was used to produce the CAT charts. Finally 584 North Atlantic (NAT), and 157 European (EUR) and Middle Eastern (MID) charts were usable. In the following analysis it will be assumed that the usable charts constitute an unbiased sample of all flights.

The CAT forecast probabilities were computed from vertical and horizontal wind shear, the vertical being the dominant contributor (see Appendix 1). At the cruising altitude band (29 000–43 000 ft) the 15-level model has a vertical resolution of about 5000 ft. Computation of vertical shears entails a considerable degree of smoothing, thus making the vertical resolution of the CAT index rather poor. The horizontal resolution is, however, good, since the index is based on 15-level model winds which are held on a 1½° latitude by 1⅞° longitude grid. CAT probability values are produced at each grid point on standard pressure levels (200, 250, 300 mb). However, owing to the poor vertical resolution, only a single level was used in the trial. Initially this was the 250 mb level, but from 12 December a new chart showing the average of the 200, 250 and 300 mb probabilities was produced for the remainder of the trial.

To simplify the chart as much as possible, the only contours marked were those representing probabilities significantly higher than the background value, which is about 2%. Initially these were the 3% and 6% contours but with the introduction of the new program in December the general appearance of the chart was improved and the overall probability levels were raised slightly making it more useful to contour the 4% and 6% values.

Fig. 1 shows the 24-hour CAT probability forecast chart valid at 0000 GMT on 3 January, which was carried on a flight departing from London/Heathrow at 1830 GMT bound for New York. The route and the pilot's remarks are shown. At any particular point the probability is that of encountering moderate or severe CAT per 100 km of flight path. To obtain the probability (P) for a longer section of flight path, the individual probabilities (p_i) are combined as follows:

$$1 - P = (1 - p_1)(1 - p_2) \ldots (1 - p_n).$$

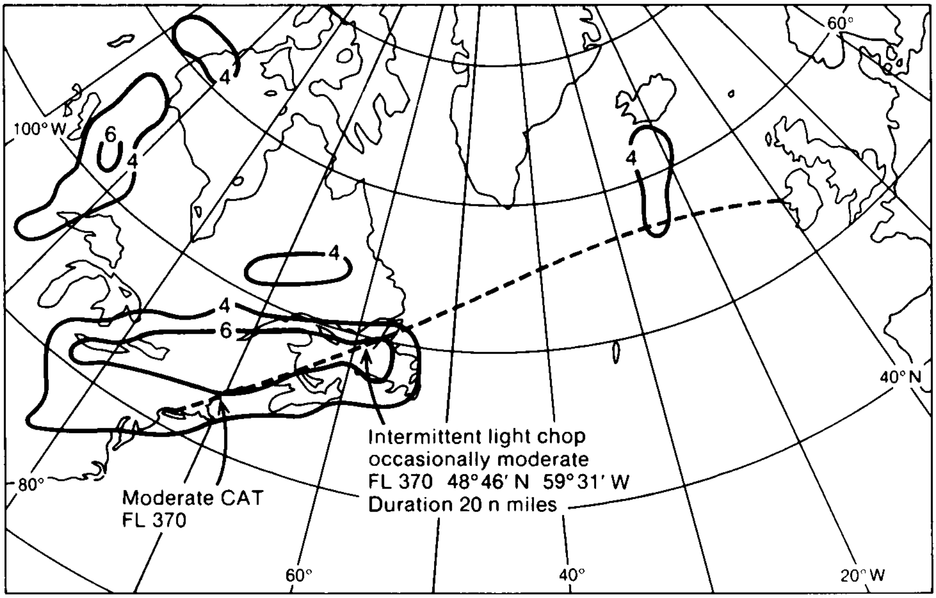

Figure 1. 24-hour CAT probability (%) forecast chart for 0000 GMT on 3 January 1985 with route of flight and pilot's remarks shown.

For example, 4% per 100 km becomes 18% over 500 km and 34% over 1000 km; 6% per 100 km becomes 27% over 500 km and 46% over 1000 km.

A criticism that may be raised against the present study is that the North Atlantic results are based entirely on westbound flights. It can be argued that eastbound flights experience more turbulence because, on average, their routes keep closer to the favourable jet core. However, since the jets coincide, on average, with the areas of highest CAT probability, it is felt that this is not too serious a criticism. In the 1976 survey, both eastbound and westbound flights were included.

Analysis of the charts

The flights were divided into the following groups:

(i)	BA—NAT	July–12 December 1984	88 flights
(ii)	BA—NAT	13 December 1984–2 February 1985	95 flights
(iii)	BA—NAT	13 February–July 1985	142 flights
(iv)	PA—NAT	February–July 1985	154 flights
(v)	AC—NAT	April–July 1985	105 flights
(vi)	BA—EUR	July–December 1984	67 flights
(vii)	BA—MID	December 1984–July 1985	90 flights

To analyse the charts, each route was divided into 100 km segments, and each segment was classified according to forecast CAT probability (low, medium or high) and turbulence experienced (nil, light, moderate or severe). This information, originally in the form of 3 × 4 contingency tables, is summarized as a set of 2 × 2 tables for each of the above groups (Tables I–VII) and for all NAT flights (Table VIII). From these a skill score (R) can be computed (see Appendix 2). If R is large then the chance of encountering moderate or severe CAT within high forecast probability areas is much greater than that of encountering it within low forecast probability areas. Also a chi-square (χ^2) test can be carried out to test

Table I. *Frequency of occurrence of CAT for British Airways flights on North Atlantic routes July–December 1984. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–3%	>3%	All
Nil or light	3969	825	4794
Moderate or severe	135	94	229
All	4104	919	5023

$P_L = 3.3\%$ $P_H = 10.2\%$ $P_B = 4.6\%$ $R_L = 0.7$ $R_H = 2.2$ $R = 3.1$ $\chi^2 = 83$

Table II. *Frequency of occurrence of CAT for British Airways flights on North Atlantic routes December 1984–February 1985. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–4%	>4%	All
Nil or light	5082	478	5560
Moderate or severe	91	77	168
All	5173	555	5728

$P_L = 1.8\%$ $P_H = 13.9\%$ $P_B = 2.9\%$ $R_L = 0.6$ $R_H = 4.7$ $R = 7.9$ $\chi^2 = 258$

Table III. *Frequency of occurrence of CAT for British Airways flights on North Atlantic routes February–July 1985. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–4%	>4%	All
Nil or light	8455	705	9160
Moderate or severe	112	37	149
All	8567	742	9309

$P_L = 1.3\%$ $P_H = 5.0\%$ $P_B = 1.6\%$ $R_L = 0.8$ $R_H = 3.1$ $R = 3.8$ $\chi^2 = 59$

Table IV. *Frequency of occurrence of CAT for Pan American flights on North Atlantic routes February–July 1985. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–4%	>4%	All
Nil or light	8980	769	9749
Moderate or severe	108	32	140
All	9088	801	9889

$P_L = 1.2\%$ $P_H = 4.0\%$ $P_B = 1.4\%$ $R_L = 0.8$ $R_H = 2.8$ $R = 3.3$ $\chi^2 = 42$

Table V. *Frequency of occurrence of CAT for Air Canada flights on North Atlantic routes April–July 1985. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–4%	>4%	All
Nil or light	6964	311	7275
Moderate or severe	27	4	31
All	6991	315	7306

$P_L = 0.4\%$ $P_H = 1.3\%$ $P_B = 0.4\%$ $R_L = 0.9$ $R_H = 3.0$ $R = 3.2$ $\chi^2 = 5.5$

Table VI. *Frequency of occurrence of CAT for British Airways flights on European routes July–December 1984. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–3%	>3%	All
Nil or light	1450	249	1699
Moderate or severe	24	30	54
All	1474	279	1753

$P_L = 1.6\%$ $P_H = 10.7\%$ $P_B = 3.1\%$ $R_L = 0.5$ $R_H = 3.5$ $R = 6.6$ $\chi^2 = 65$

Table VII. *Frequency of occurrence of CAT for British Airways flights on Middle Eastern routes December 1984–July 1985. Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast 0–4%	>4%	All
Nil or light	4002	203	4205
Moderate or severe	109	10	119
All	4111	213	4324

$P_L = 2.6\%$ $P_H = 4.7\%$ $P_B = 2.7\%$ $R_L = 1.0$ $R_H = 1.7$ $R = 1.7$ $\chi^2 = 3.2$

if there is any relationship between forecast and experience. It must be stressed that the analysis is completely objective, and no account is taken of 'near misses'.

A difficulty in the interpretation of the turbulence reports was encountered for some of the flights. A few pilots chose to use a symbol to indicate turbulence, and it became clear that different pilots were using the same symbol with different meanings*. In all, 24 reports were found to be ambiguous.

Several comments on the effectiveness of the charts were received. These were mainly complimentary, except one that exhibited concern from a legalistic viewpoint at the introduction of probability turbulence forecasting. Further comments were made on the presentation of the charts, and these pointed out some weaknesses which have since been remedied.

* The official World Meteorological Organization/International Civil Aviation Organization symbols are for moderate and for severe, but before about 1960 the symbols were for light, for moderate and for severe.

Table VIII. *Frequency of occurrence of CAT for all flights on North Atlantic routes July 1984–July 1985 (the 3% probability level was used up to 12 December 1984, but was replaced by the 4% level after that date). Probability, usefulness and skill score of forecasts are listed below the table (see Appendix 2 for explanation of notation)*

Reported turbulence	CAT probability forecast		
	0–3% 0–4%	>3% >4%	All
Nil or light	33 450	3 088	36 538
Moderate or severe	473	244	717
All	33 923	3 332	37 255

$P_L = 1.4\%$ $P_H = 7.3\%$ $P_B = 1.9\%$ $R_L = 0.7$ $R_H = 3.8$ $R = 5.4$ $\chi^2 = 565$

Results

Tables I–V and Table VIII show that over the North Atlantic and North America R was very high (7.9) in winter and ranged from 3.1 to 3.8 throughout the rest of the year, averaging 5.4 over the whole year. This high degree of skill is borne out by the results of χ^2 tests on the 2×2 contingency tables. All show significance at the 5% level and all except Table V show significance at the 0.1% level. Table V covers the summer period when there were rather few reports of moderate turbulence (and none of severe). Although less successful in the sense that only 4 out of the 31 turbulent route segments fell in areas of medium to high probability (> 4%), the amount of the area forecast to be above 4% was substantially smaller than that during the other periods.

Table VI shows that over Europe the skill is also high ($R = 6.6$ and $\chi^2 = 65$). Table VII, however, shows that over the Middle East the skill is rather poor ($R = 1.7$ and $\chi^2 = 3.2$). Much of the turbulence experienced on these flights would appear to be topographically related.

Examination of the 3×3 contingency tables obtained from the original 3×4 tables by combining moderate and severe CAT into a single category shows, using χ^2 tests, significant skill in forecasting light turbulence (as well as moderate to severe). It also demonstrates that the skill in forecasting moderate to severe turbulence exists in both medium probabilities (4–6%) and high probabilities (> 6%).

To demonstrate that the ambiguity in the interpretation of the turbulence symbol had not significantly biased the results, another set of 2×2 contingency tables was constructed by grouping together all turbulence (light, moderate and severe). The R values corresponding to Tables I–VIII are, respectively, 2.4, 4.6, 3.4, 3.4, 4.5, 4.1, 2.2 and 3.8 and the corresponding χ^2 values 97, 307, 134, 164, 95, 84, 17 and 927. While not quite so prominent as before, the winter period still stands out strikingly. Significant skill in forecasting light turbulence is also shown in the summer period. (It should be noted that the χ^2 values for the individual tables cannot be directly compared since the marginals and totals in the tables are not identical.)

As mentioned in the Introduction, a limited comparison of objective and subjective CAT forecast charts was carried out in 1983. For each of five selected days (30 and 31 December 1982 and 4, 9 and 16 January 1983) all aircraft reports from flight levels in the band 29 000–43 000 ft within a specified area of the North Atlantic (30–70° N, 0–60° W) for the period 09–15 GMT were scrutinized. Reports of moderate or severe turbulence during the 6-hour periods were correlated with both the objective 24-hour forecast CAT chart valid at 1200 GMT, and the subjectively prepared CAT chart for the same time. The 2×2 contingency tables obtained are given in Table IX. Although the 'success' in forecasting moderate or severe CAT appears marginally worse in the objective method (10 out of 22) when compared with the

Table IX. *Comparison of objective and subjective CAT forecasts made in 1983 using selected aircraft reports over the North Atlantic. Probability, usefulness and skill score of forecasts are listed below the tables (see Appendix 2 for explanation of notation)*

Reported turbulence	Objective CAT probability forecast 0–3%	>3%	All
Nil or light	528	91	619
Moderate or severe	12	10	22
All	540	101	641

$P_L = 2.2\%$ $P_H = 9.9\%$ $P_B = 3.4\%$ $R_L = 0.6$ $R_H = 2.9$ $R = 4.4$ $\chi^2 = 15$

Reported turbulence	Subjective CAT forecast No	Yes	All
Nil or light	369	250	619
Moderate or severe	11	11	22
All	380	261	641

$P_L = 2.9\%$ $P_H = 4.2\%$ $P_B = 3.4\%$ $R_L = 0.8$ $R_H = 1.2$ $R = 1.5$ $\chi^2 = 0.8$

subjective method (11 out of 22), it is to be noted that the number of all reports which occur in areas of high forecast CAT probability in the objective method is only 16% (101/641), substantially smaller than the number of all reports in areas of forecast CAT ('yes' areas) in the subjective method, which is 41% (261/641). Therein lies a significant improvement in skill. For the objective forecasts R is 4.4, but for the subjective forecasts only 1.5; χ^2 values are 15 and 0.8 respectively. These results for the subjective forecasts agree closely with those obtained for the North Atlantic using data from the 1976 survey (Dutton 1979). No comparison with the subjective forecast has been attempted in the current study, since the forecaster is now making more use of the objective forecast charts in the preparation of his forecast.

Conclusions

The results of this study demonstrate an encouraging degree of skill in the current Meteorological Office automated 18- and 24-hour CAT forecasting program and are in general agreement with the results of a previous study based on the 1976 survey, thus demonstrating that the regression equation devised for the old 100 km limited-area 10-level model can be used with confidence for the new 150 km global 15-level model.

Acknowledgements

The author wishes to express his thanks to the many pilots who took the trouble to complete and return the charts, to John Rankin of British Airways for organizing the trial, and to the staff at the meteorological office at London/Heathrow for distributing the charts.

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1980 Probability forecasts of clear-air turbulence based on numerical model output. *Meteorol Mag*, **109**, 293–310.

Appendix 1 — *CAT index*

Based on the pilots' reports from the 1976 North Atlantic Turbulence Survey together with forecasts from the operational limited-area 100 km mesh 10-level model, and using statistical multiple regression techniques, Dutton (1980) developed a predictive equation for the probability of moderate or severe CAT in terms of vertical and horizontal wind shear. The CAT index E is given by:

$$E = 1.25\ S_H + 0.25 S_V^2 + 10.5$$

where S_H is the horizontal wind shear in m s^{-1}/100 km and S_V is the vertical wind shear in m s^{-1}/km.

The index E is converted to the probability p of encountering moderate or severe CAT per 100 km of flight path using the values given in Table AI. If $E \leq 5$ then p is set to 0.0% and if $E \geq 30$ then p is set to 7.5%. The average, or background, value of p is about 2.0%. Thus only areas where the probability is forecast to be significantly higher (or lower) than this background value are actually useful. The table also lists values of the model wind shears which can produce various values of E and p.

Table AI. *Values of E and corresponding p values which can be produced by given model wind shear values*

E	p(%)	S_V (if $S_H = 0$) m s^{-1}/km	S_V (if $S_H = 0$) kn/1000 ft	S_H (if $S_V = 0$) m s^{-1}/100 km	S_H (if $S_V = 0$) kn/100 n mile
5	0.0	—	—	−4.4	−15.8
7.5	0.95	—	—	−2.4	−8.6
10	1.55	—	—	−0.4	−1.4
15	2.2	4.2	2.5	3.6	13.0
20	2.8	6.2	3.7	7.6	27.4
25	4.2	7.6	4.5	11.6	41.8
30	7.5	8.8	5.2	15.6	56.2

Appendix 2 — *Contingency tables and use of* χ^2 *test*

The general 2 × 2 contingency table can be written in the form:

Reported turbulence	CAT probability forecast 0–4%	CAT probability forecast >4%	All
Nil or light	a	b	r_1
Moderate or severe	c	d	r_2
All	s_1	s_2	N

where a, b, c and d are cell frequencies, the marginal frequencies r_1 and r_2 are row totals, s_1 and s_2 are column totals, and N is the sum of all cell frequencies.

From these tables, it is straightforward to compute the percentage probabilities of encountering moderate or severe CAT in regions of low forecast probability ($P_L = c/s_1$) and high forecast probability ($P_H = d/s_2$). The background probability ($P_B = r_2/N$) is defined as the overall frequency of reports of moderate or severe CAT. The ratios of the conditional probabilities (P_L and P_H) to the background probability (P_B) can be used as a measure of the usefulness of the forecast (R_L and R_H), and the ratio of these can be regarded as a skill score (R), i.e. $R_L = P_L/P_B$, $R_H = P_H/P_B$ and $R = R_H/R_L$.

A χ^2 test, based on the null hypothesis that there is no relationship between forecast and experience, was carried out on each of the contingency tables. If there is no skill in the forecast, then the expected cell frequencies, given fixed marginals r_i and s_j, would be

$$E_{ij} = r_i s_j / N.$$

These can be compared with the observed frequencies O_{ij} by computing

$$\chi^2 = \sum_{ij} (O_{ij} - E_{ij})^2 / E_{ij}.$$

For a 2×2 table, which has one degree of freedom, a value of χ^2 greater than 3.8 indicates significance at the 5% level, and a value greater than 10.8 indicates significance at the 0.1% level.

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Errors in height estimation of convective cloud base

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Summary

Glider pilots have reported that the base of cumulus clouds over England is frequently found to be much higher than that reported by nearby ground observers. It has been found that condensation levels calculated from screen dry-bulb and dew-point data are generally closer to the true cloud base. It is suggested that estimations of cumulus bases would be improved if observers first calculated the condensation level.

Introduction

In spite of major developments in weather-sensing systems, the meteorological observer remains an important source of data for analytical work and forecasting. Almost all of the synoptic report is based on the use of measuring instruments but one section of it is largely dependent on the observer's judgement. This is the height of the cloud base, which is especially difficult to estimate during the daytime when a cloud searchlight cannot be used.

Cloud-base recorders, such as the Meteorological Office Mk 3A, are not installed at all observing stations. Although these instruments are excellent for measuring the height of continuous cloud cover, especially below 2000 ft, they suffer from progressively larger errors with height. At the top of the scale (4000 ft) the instrumental error, according to Douglas and Offiler (1978), is about minus 1332 ft. As it is necesssary for the cloud to pass directly over the vertical beam, this system is ill-adapted for recording well-broken cumulus above 3000 ft. In this instance the observer is obliged to make an estimate by eye.

Measurement of cloud base by glider pilots shows that an observer's estimate is often well below the true value. It has been noted, however, that the dry- and wet-bulb temperatures in the thermometer screen are an indication of the height of the convective cloud base. George (1970) published a diagram to calculate dew-point, relative humidity and convective cloud base from these measurements, but lacked supporting evidence of measurements from aircraft.

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A quick estimate of the cloud base is obtainable from the simple formula $(T - T_d) \times 400$ t, where T is the air temperature and T_d the dew-point at screen level. It has been found, over very many years of flying by the author, that this formula is capable of producing remarkably accurate results. It was therefore decided to carry out an investigation to determine the accuracy of observers' estimates, and to compare these with calculated values based on dry- and wet-bulb temperature readings.

Collection and comparison of data

The data used were recorded during glider flights over southern England between 1982 and 1985. Whenever the convective cloud base was reached, the height and position of the aircraft were noted, and also the time. A total of 37 observations was made. After each flight the relevant southern England surface synoptic charts were examined, and data extracted from the nearest ground observing station(s). For example, an airborne observation was made at 1230 GMT on 18 August 1983 near Market Harborough, and the 1300 GMT observational data of cumulus base, temperature and dew-point were noted for Birmingham and Bedford. If the airborne observation was made within five miles of a reporting station, that station alone was used for comparison purposes. In all other cases mean values of reported cloud height, temperature and dew-point were worked out, this being the nearest approximation to that which an observer below the glider would have reported. All values of cloud height, both observed and calculated, were converted to heights above mean sea level.

Fig. 1 illustrates the comparison between ground observers' estimates of the height of the cumulus base with that observed in the air. With the exception of four observations, all estimates of cumulus height above ground level lie beneath the correct estimate line. Extreme values are plus 16% and minus 55%, and the calculated mean deviation is minus 700 ft. This clearly indicates that a substantial proportion of observers underestimate the true height by at least 12% for cumulus which is above 3000 ft.

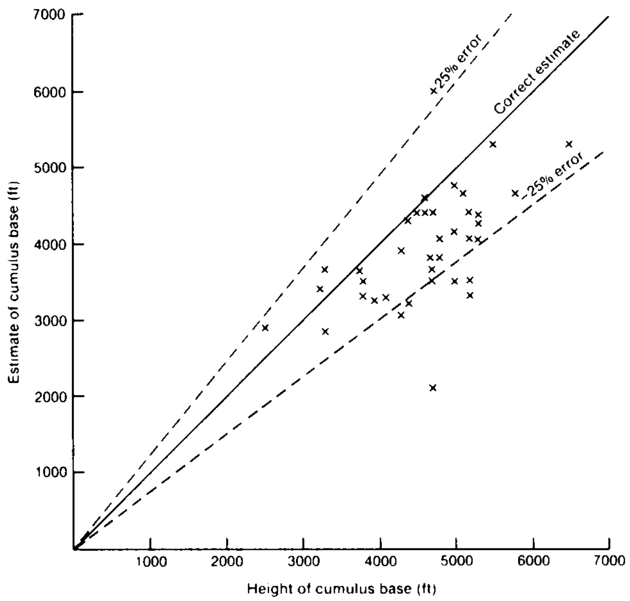

Figure 1. Plot of ground observers' estimates of cloud base height against height measured during glider flights. All heights above mean sea level.

Fig. 2 shows a plot of calculated convective cloud bases, using the formula $(T - T_d) \times 400 + H$ (where H is the height of the station above mean sea level), against those observed in the air. The scatter of plots is evenly distributed about the correct estimate line, the extreme values being plus 20% and minus 20%, and the calculated mean deviation minus 13 ft. Only four plots out of the total of 37 show an error exceeding 500 ft.

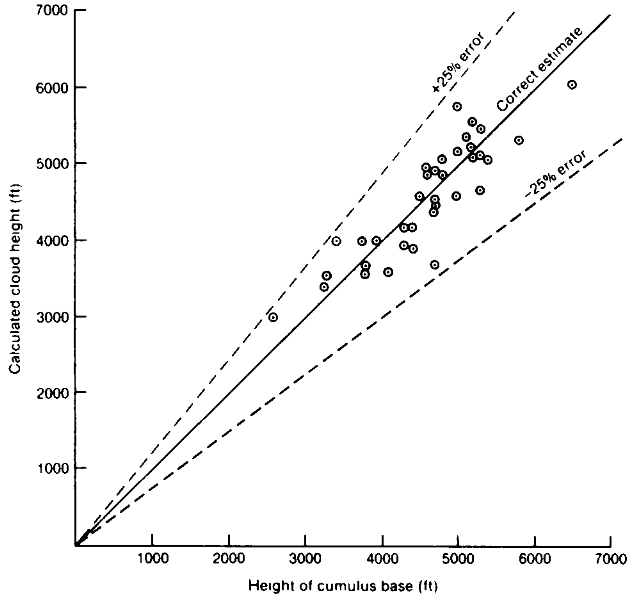

Figure 2. Plot of calculated cloud height against cloud base height measured during glider flights. All heights above mean sea level.

Possible data errors

The errors encountered in this investigation can conveniently be split into three types:

(i) *Instrumental and observing errors*. In the glider the height of the cumulus base was read from a standard aircraft altimeter which is checked annually; the maximum calibration error permitted is 50 ft in 5000. It is often found that the cloud base is rather diffuse so that a pilot may not be able to determine the exact height to better than ± 50 ft. It is therefore reasonable to assume that the height is within ± 100 ft of the true value, and that the errors of measurement are not significant over the range of heights encountered.

(ii) *Pressure setting errors*. The surface pressure fields were examined on each occasion to determine what changes took place over the area covered during the period of the flight. Any errors due to changes of mean-sea-level pressure were within ± 100 ft.

(iii) *Errors due to time and distance from ground observers*. Since airborne and ground-based observations were not usually synchronous, and there was no guarantee that an airborne observation would be taken directly above a ground station, comparisons of the observations may produce a biased result. In extreme cases daytime heating may raise the cloud base by as much as 1500 ft in an hour. However, it was judged that in most cases individual errors were unlikely to exceed ± 300 ft, and therefore the mean error was not significantly biased. It is perhaps worth noting that the worst plot (Fig. 1) came from an observation made within three miles of the nearest ground observing station, and within ten minutes of the normal observation time.

Discussion

The main conclusion to be drawn from this research is that, in the 37 cases examined, observers would have done rather better to use the temperatures from the thermometer screen as a guide to cumulus cloud height. It is worth considering why observers frequently underestimate the true height.

Perhaps the largest single factor is lack of regular feedback. Although meteorological observing stations on airfields occasionally receive reports of cloud height from aircraft, most of these occur when conditions inhibit flight operations. Cumulus, except in unusual circumstances, does not constitute a problem to aircraft operating in an airfield circuit or approach pattern. Without these reports, or any other source of height check, it is inevitable that errors occur. The fact that the ground-based observers usually underestimate the cloud base is probably due to a feeling that it is better to err on the low side on somewhat questionable safety grounds.

Rapid increases in cumulus base may outpace the observer's successive hourly reports. Rises of 2.5 °C per hour are not that uncommon in summer, resulting in a change of 1000 ft in the cloud base (provided the dew-point remains the same). The observer may not recognize by eye alone the magnitude of this change.

When the cumulus base occurs in the range 6000 to 8000 ft it is not surprising that observers fail to report with any consistent accuracy. Indeed, it would be very difficult for any observer to be able to differentiate between one cloud at 6000 ft and another at 8000 ft as the appearance would be almost identical. The magnitude of observational error for cloud at 6000 ft and above is illustrated in Table I. A random selection of 369 reports was taken from surface UK charts for 1500 GMT for the period May to August 1976, each report exhibiting at least 15 °C difference between air temperature and dew-point in conjunction with cumulus or altocumulus cloud. On the basis that the calculated value gives a correct height within 500 ft, then the bulk of reported heights are between 1000 and 2000 ft too low. Some 10% of reports in the sample show errors of as much as half the true height.

Table I. *Comparison of reported cloud base height with calculated height using a random sample of observations extracted from months May to August 1976 when air temperature and dew-point difference equalled or exceeded 15 °C in conjunction with cumulus or altocumulus cloud (total sample 369)*

Reported temperature difference and calculated height °C	ft	Reported cumulus or altocumulus height (ft) at 1500 GMT < 4000	4000–4400	4500–4900	5000	6000	7000	8000	9000	10 000
26	10 400	0	0	0	0	1	0	0	0	0*
25	10 000	0	0	0	0	1	0	0	0	0*
24	9 600	1	0	1	1	0	0	0	0	0*
23	9 200	1	1	0	1	3	1	0	0*	0
22	8 800	0	1	0	5	6	3	1	0*	0
21	8 400	1	4	3	9	7	1	0*	0	0
20	8 000	1	1	2	8	12	2	0*	0	0
19	7 600	3	7	5	9	10	4	0*	0	0
18	7 200	3	4	5	22	14	1*	0	0	0
17	6 800	6	8	10	6	9	0*	0	0	0
16	6 400	5	10	11	28	16*	1	0	0	0
15	6 000	13	20	17	33	10*	0	0	0	0

* indicates correlation between reported cloud height and calculated cloud height (within 500 ft)

The *Observer's handbook* (Meteorological Office 1982) quotes 1000–6500 ft as the 'wider range of height of base sometimes observed'. However, there have been a number of reports by glider pilots which confirms the existence of cumulus above 8000 ft*. Although these are few and far between, the surface temperature and dew-point differences in Table I (up to 26 °C) make 10 000 ft quite feasible provided the vertical temperature profile is favourable. Indeed, unconfirmed reports suggest that convective cloud formed at 11 000 ft on one day during the summer of 1976.

Advice to meteorological observers

It is quite clear that the human eye has severe drawbacks when applied to estimating height of cloud above ground level. It relies on relative shape, size, outline structure and speed of movement, and no two observers are likely to agree. Although cloud below 3000 ft can be estimated fairly accurately in absolute terms, guidance is clearly required for higher levels. The screen temperatures will provide that help with respect to cumulus cloud.

There are however some provisos. The screen temperatures may not be representative of the air reaching the condensation level over the whole sky, especially near coasts or in mountainous regions. For example, a sea-breeze front can exhibit as much as a 2000 ft change in convective cloud base in a matter of a few hundred yards. The onset of showers will result in marked fluctuations in both air temperature and dew-point values and, until the effects have passed and the ground has largely dried out, the calculation of cumulus height is likely to give a false value. It is recommended that the calculation method is confined to periods of the day when the temperature is rising. There is some evidence to suggest that once the temperature has passed its peak and begun to fall, it no longer gives as accurate a guide.

One final word of warning. Although it is possible to use the screen temperatures as a guide to the height of stratiform type clouds, there will be many occasions when the two are not correlated. It is not recommended as a general practice.

Acknowledgement

The author is indebted to Mr T.A.M. Bradbury for his advice in the preparation of this article.

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* On 8 August 1975 the author found the cumulus base to be 8300 ft above mean sea level near Brize Norton (surface air temperature 33 °C, dew-point 12 °C).

551.515.427:551.558.1

Daytime peninsula convection — 13 May 1986

By the Satellite and Radar Studies Group
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Satellite and radar pictures taken when there is an unstable polar airstream over the British Isles indicate that the distribution of convective cloud and showers is rarely randomly scattered. Whether the air mass is unstable to sea temperatures, land temperatures or both, distinct lines or bands of convection lying parallel to low-level winds are usually clearly evident. For example, a persistent feature during north-westerly winds in the winter season, when the air is unstable to sea temperatures, is a line of showers emanating from the North Channel between Scotland and Northern Ireland (Browning *et al.* 1985)*. Significant lines of cloud and precipitation are also observed over land during spring and summer following daytime heating.

South-westerly airstreams of polar maritime origin occurred frequently over southern and central Britain during the spring of 1986. Convective clouds and showers sometimes occurred over the sea, mostly as comma-shaped clusters, but most convection took place over land during the day. May 13 was typical of such days, the mid-afternoon distribution of cloud and rain being shown in Figs 1 to 3. Early in the day, convection occurred over western areas of the British Isles, particularly near high ground such as over Wales, but by early afternoon much of mid-Wales had become cloud free with the convection

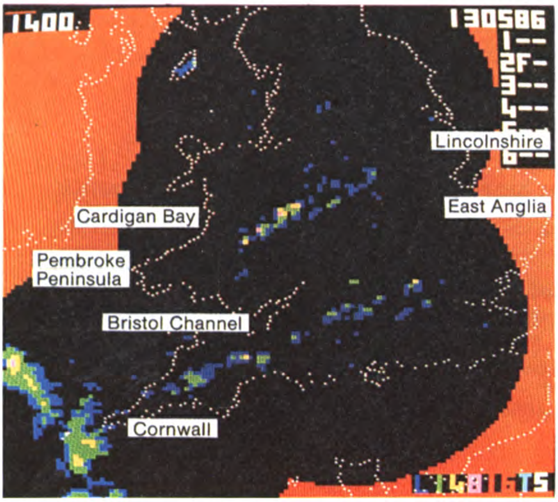


Figure 1. Radar network picture at 1400 GMT 13 May 1986. Rainfall intensities are indicated by colours as follows: dark blue = < 1 mm h^{-1}, green = 1–4 mm h^{-1}, yellow = 4–8 mm h^{-1} and magenta = 8–16 mm h^{-1}. (Precipitation was not observed over south-east England owing to blocking of the radar beam by high ground.)

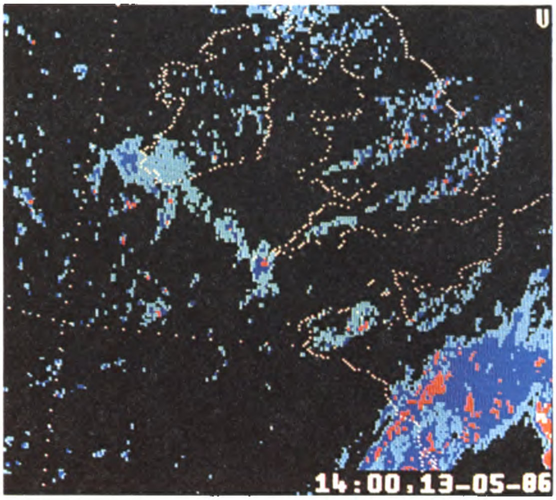
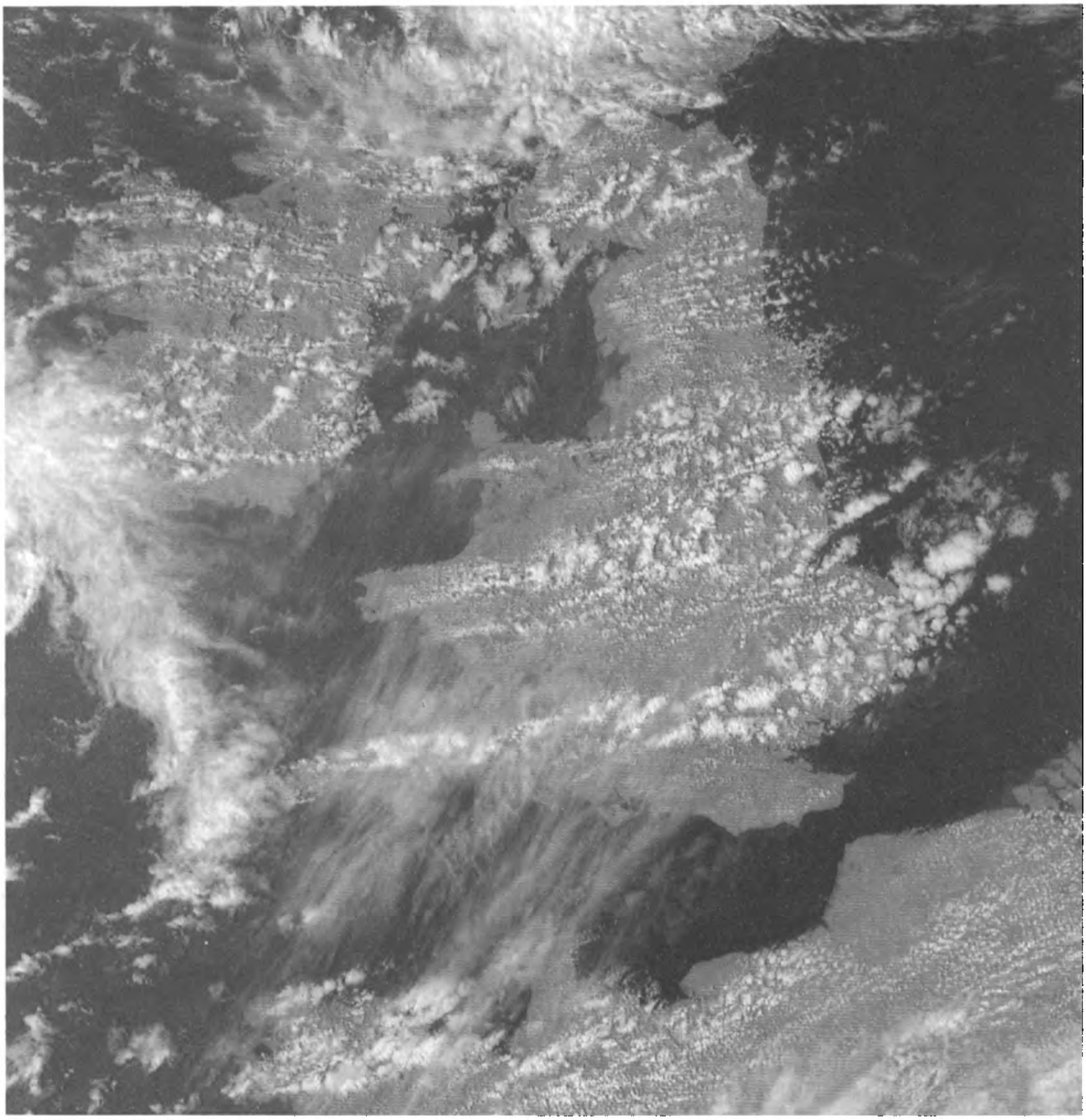


Figure 2. Digitized Meteosat image at 1400 GMT 13 May 1986. Colours indicate cloud thickness; pale blue represents thinner cloud, red represents thickest cloud. The data have been re-projected on to the same grid as the radar picture (Fig. 1) allowing direct comparison of cloud and rain data.

* Browning, K.A., Eccleston, A.J. and Monk, G.A.; The use of satellite and radar imagery to identify persistent shower bands downwind of the North Channel. *Meteorol Mag*, **114**, 1985, 325–331.



Photograph by courtesy of University of Dundee

Figure 3. NOAA-9 visible image at 1406 GMT 13 May 1986.

being aligned in bands along the wind direction. Additionally, two other areas of convection were present; one over East Anglia and one west of Cornwall. The broad area of convection over East Anglia, seemingly related to the band downwind of the south-west peninsula, actually developed separately over south-east England near the remains of a weak surface trough that had been tracked by radar from west to east across Britain during the previous 12–18 hours. The band of convective precipitation which lay over the sea immediately west of Cornwall was associated with another minor trough.

With the exception of that over East Anglia, the convection over land was clearly organized into bands extending downwind from major peninsulas. The radar network picture at 1400 GMT (Fig. 1) indicates that all precipitation over land was confined within two well-defined bands originating over the Cornish and Pembroke peninsulas. The NOAA-9 image at 1406 GMT (Fig. 3) clearly indicates the overall pattern of convection, but also shows distinct cloud-free wedges. The major cloud-free areas are immediately downwind of the Bristol Channel and Cardigan Bay. Close examination of this image, however, also shows smaller-scale cloud lines and clear slots.

The Meteosat digitized visible image at 1400 GMT (Fig. 2) gives an indication of the thickest (brightest) cloud. In this image, all sea, land and thin cloud has been set to black, with the remaining thick cloud colour-coded. Comparison of the image and the corresponding radar picture (Fig. 1) shows that the brightest clouds are well correlated with showers. The first indication of the formation of distinct cloud and shower lines was observed at about 1300 GMT, with a maximum intensity of precipitation at or soon after 1500 GMT. The organization decayed rapidly soon after 1700 GMT.

During May 1986, the line of cloud from the south-west peninsula was a frequent occurrence, having been observed on seven out of the eight afternoons on which relatively cloud-free polar air masses reached Cornwall from the south-west. On the one day that the cloud line failed to appear, a slow-moving weak cold front was close by. The Pembroke cloud line was less persistent, having been clearly observed on only four out of the eight occasions. The orientation of the cloud lines varies slightly depending on the wind direction. In a west-south-westerly airstream, such as occurred on 13 May, the south-west peninsula line may well reach London, whilst in a south-south-westerly airstream it has been observed to extend across central England towards Lincolnshire. Occasionally cloud has extended as far as the North Sea before dissipating. Generally the Pembroke line has not been observed to extend as far downwind, although it does seem to have the same range of orientations as the south-west peninsula line. The cloud lines need not necessarily be associated with precipitation —in dry air masses they may be composed of shallow convective cloud. On the other hand, the convective clouds may be associated with a well-marked line of showers. In the example illustrated, inland locations within the convective bands had frequent heavy showers throughout the afternoon while other places, a few tens of kilometres north and south, had a dry sunny afternoon.

The origin of the cloud lines appears to be closely correlated with sea-breeze circulations, with the afternoon maximum of the onshore wind component leading to convergence over peninsulas and the possible formation of cloud and showers. Conversely, significant bays will tend to be regions of divergence, the resulting descent suppressing convection, thereby leading to the formation of cloud-free slots.

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A case study of the detection of fog at night using channels 3 and 4 on the Advanced Very High Resolution Radiometer (AVHRR)

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Summary

An image created from Advanced Very High Resolution Radiometer satellite imagery using a bi-spectral technique is able to provide detail of fog cover not possible by conventional means. Comparison with surface observations is examined in detail on an occasion of patchy fog over England and Wales.

1. Introduction

Eyre *et al.* (1984) described a new technique for the detection of fog at night using two of the infra-red channels on the Advanced Very High Resolution Radiometer (AVHRR), flown on the TIROS-N series of polar-orbiting satellites. This bi-spectral technique identified the areas covered by fog by using the fact that water clouds, including fog, have a lower apparent temperature in one of the infra-red channels than in the other. Land and sea surfaces have similar apparent temperatures in both channels.

In general, objects emit electromagnetic radiation that is characteristic of their temperatures. By measuring that radiation, it is possible to determine their temperatures.

An object at a certain temperature can emit up to a maximum amount of radiation, this limit being given by Planck's law (Houghton 1977). The hypothetical objects that emit this maximum amount are known as 'black bodies'. It is found that real objects radiate less efficiently than would be predicted by Planck's law. This efficiency is known as the 'emissivity'. The 'brightness temperature' of an object is the temperature of a black body that emits the same amount of radiation as the real object; the physical temperatures of real objects are higher than their brightness temperatures. In an accurate computation of the temperature of an object from its emitted radiation, an allowance would have to be made for this efficiency.

The AVHRR radiance measurements from channels 3 (3.7 μm) and 4 (11 μm) can be calibrated using data from the views of deep space and the on-board calibration targets to obtain brightness temperatures in the two infra-red channels. These can then be compared for each pixel (picture element). Theoretical considerations suggest that the magnitude of the difference would give some indication of the vertical thickness of the fog.

Eyre *et al.* (1984) included an example from August 1981 in which a composite image had been created to show the temperature of areas covered by fog or low stratus in shades of grey, with the surface temperatures in clear areas in various colours. In the present study, it was decided to investigate in more detail the relationship between the magnitude of the temperature difference between the two AVHRR channels and conventional observations of the distribution of and horizontal visibility in the fog. It was hoped that this procedure would yield a threshold temperature difference for use in future operational products for forecasters.

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2. The case study — 23 October 1983

A case study was selected by examining the operational charts held at the Meteorological Office Archives. The aim was to find a case in which there was patchy fog across the country rather than widespread coverage since it was felt that one of the main advantages of the detection of fog using satellite techniques was that much more detail could be provided on the spatial coverage than was possible using conventional data. It was found that 23 October 1983 fulfilled these requirements.

The raw AVHRR data were obtained from the University of Dundee and processed on the HERMES (High-resolution Evaluation of Radiances from MEteorological Satellites) system in the Satellite Meteorology Branch of the Meteorological Office (Turner *et al.* 1985). All of the relevant conventional data were obtained for the period of the study.

At 0600 GMT on the 23 October 1983, a large anticyclone with mean-sea-level pressures up to 1039 mb was centred over south-east Europe with a ridge extending west-north-westwards into central and southern England. A frontal trough lay across Northern Ireland and north-east Scotland and this moved eastwards to cross most of the United Kingdom during the day.

The UK chart for 0500 GMT (Fig. 1) shows virtually no cloud over England, Wales and northern France. Strong to gale force south-westerly winds persisted in the north of Scotland but over central and southern England the winds were mainly south to south-easterly, with speeds of 5 kn or less.

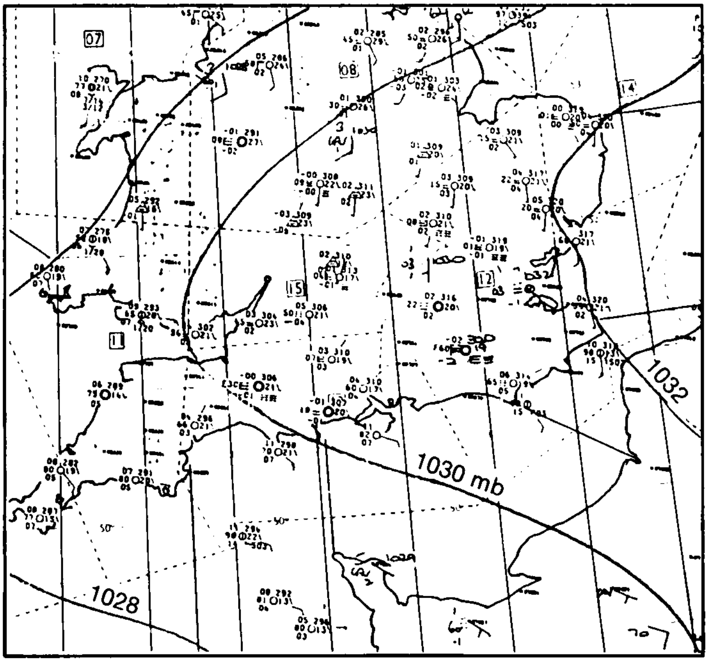

Figure 1. Surface analysis and observations at 0500 GMT 23 October 1983.

3. Analysis of fog cover

(a) *From surface observations*

At midnight, fog was reported only from Coltishall and Gatwick, both with the sky visible, although there was mist reported in northern England, Dorset and in a belt across East Anglia and central

England. There was very little increase in the size of the areas covered by fog until after 0200 GMT. By 0500 GMT, fog was reported at most inland stations in the south-east.

Since variations in visibility can occur on a scale much smaller than that of the synoptic network, it is extremely difficult to produce an accurate analysis of fog coverage from the surface reporting stations alone. The observations at 0500 GMT (Fig. 1) show, apparently, three main areas of fog: the Somerset/Dorset area, the north-east coast of East Anglia and in an arc through Northamptonshire, London and Surrey. The south, east and western coasts generally had good visibility at this time, but in central areas of England, the visibilities reported were very variable.

(b) *From the satellite imagery*

On 23 October 1983, a NOAA-7 satellite passed over the United Kingdom on a south-bound orbit at about 0433 GMT. The digital measurements of radiance from the AVHRR were calibrated over a range of 25.5 K and quantized to eight bits. The smallest detectable change in the scene temperature is about 0.1 K, approximately the level of the radiometric noise of the long-wave detectors of the instrument.

An image can be formed from the difference in the brightness temperatures viewed by the two channels for each pixel (Fig. 2) providing that certain corrections are made (Allam 1986). The contrast in this image has been selected to display a range of temperature differences from about −4.0 K to +4.5 K in steps of 0.03 K. Light areas in Fig. 2 occur where the channel 3 brightness temperatures are lower than those for channel 4 and, from both theoretical considerations and the previous study (Eyre *et al.* 1984), are indicative of fog-covered areas. The dark spots in the image occur where the channel 3 brightness temperatures are higher than those for channel 4. This situation occurs when a relatively hot object occupies a small proportion of a single pixel. Blast furnaces, gas flares and stubble fires are common causes.

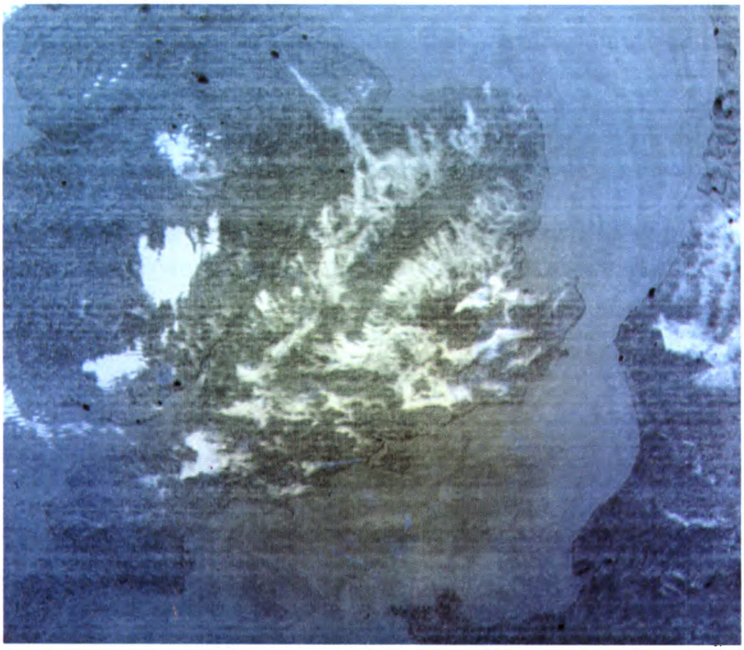

Figure 2. Satellite image for 0433 GMT 23 October 1983 formed from the brightness temperature difference between the two AVHRR channels (channel 4 − channel 3) after applying corrections. Light areas correspond to regions in which fog would be expected to occur. Dark spots indicate relatively hot areas (for example, blast furnaces).

4. Comparison of conventional data with imagery

In order to compare the details of the satellite image with conventional observations and local topography, a method was adopted of locating each pixel in the satellite image which contained an observation site. Using information on the orbit of the satellite and the geometry of the scanning pattern of the instrument, an attempt was made to compute the coordinates within the image of certain geographical locations.

Owing to errors in the knowledge of the orbit, this attempt was not completely successful. An empirical correction was obtained by comparing the computer positions of twelve prominent coastal features with their actual positions in the image. It was estimated that following this procedure a point with a specified latitude and longitude within the area of interest could be located to an accuracy of two pixels, or approximately 3 km.

The observations of weather and horizontal visibility for each station reporting at 0500 GMT were compared with the difference in brightness temperature between the two AVHRR channels. Since there were uncertainties of about two pixels in the location of the observing station within the image, it was decided to use an average temperature difference over the nine pixels closest to that predicted to contain the station. Detailed visual inspection of the images showed scattered anomalous values, attributable to noise in the raw data. The mean of the nine pixels could easily give a distorted average in an area with a few anomalous values so the median was used.

Another difficulty is that the conventional data and the satellite image are asynchronous. This could be crucial when the visibility is changing rapidly. For variables that vary smoothly in time, a method of interpolation could be used to estimate a value at any time between two observations. Since the horizontal visibility does not vary smoothly at the onset of fog, this approach could not be used. Accordingly, observations at the nearest time to the satellite pass have been used.

Fig. 3 shows the median brightness temperature difference for the nine pixels closest to the predicted point of observation plotted against the horizontal visibility for 0500 GMT. A curve that fits the points is also shown. A general increase in the value of the temperature difference is noted as the visibility decreases. At high visibilities, the mean value of the difference is about 0.4 K, suggesting that the

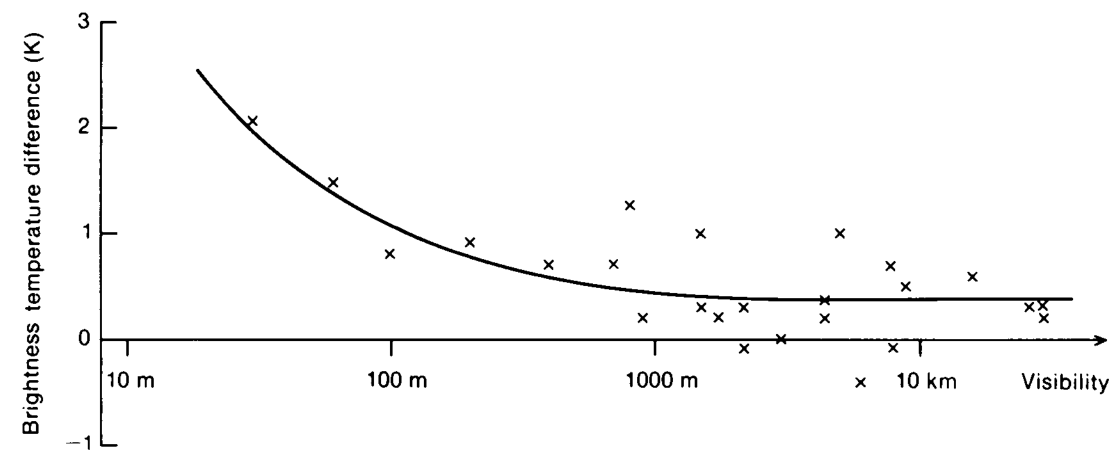

Figure 3. Graph of brightness temperature difference between the two AVHRR channels (channel 4 − channel 3) against logarithm of reported visibility at 0500 GMT 23 October 1983.

emissivity of the land is slightly different at the two wavelengths. If there was no difference in the emissivity, the mean temperature difference should be slightly negative, since a pixel containing objects with different brightness temperatures would appear warmer at 3.7 μm than at 11 μm (Saunders 1986).

It is difficult to determine a clear threshold in the difference between the brightness temperatures of the two channels that can be applied to distinguish visibilities below 1000 m from those above it. However, a difference of 1 K could be used to discriminate between visibilities above and below about 150 m, assuming that the two isolated points with visibilities greater than 150 m and differences greater than 1 K are due to noise in the validation technique.

5. Discussion of results

It should be emphasized that the bi-spectral method of detecting fog is based upon the characteristics of the liquid water in the field of view, and especially upon the drop-size distribution and total amount. While it is clear that both of these factors will affect the horizontal visibility, it is not clear that changes in them will affect equally both the radiation in the two infra-red regions used in the technique and that in the visible region used to estimate the visibility.

It should also be noted that the directions of the two types of measurement are different; the satellite observations are dependent upon the vertical, or near-vertical, distributions of liquid water and temperature, whereas visibility measured by observers on the ground is determined by the horizontal distribution of water.

Areas of shallow fog may occur that are sufficiently thick to produce a significantly different spectral signal from surrounding areas, yet may not be deep enough to cause a significant deterioration of visibility measured at the eye-level of an observer. It is also possible, particularly at night, that significant areas of fog may remain undetected by the observer. Thus the observation of visibility may not be characteristic of the region around the station.

Furthermore, the positions of most of the stations reporting fog at 0500 GMT were situated away from the coherent areas of light pixels shown in Fig. 2. The fog observed was of limited vertical extent since, in all cases, the sky was not obscured.

The satellite data are effectively averages over space. Even the pixels produced by the AVHRR, which at best are approximately 1 km square, could be expected to contain areas both with and without fog. It is unlikely that the detail of the spectral signal that is characteristic of such regions will be unravelled using the conventional observing network, but it might be possible using some sort of mathematical simulation.

6. Circumstantial evidence for fog from the image

Referring again to the image shown in Fig. 2, a number of areas of interest can be related to the local topography and conventional observations.

In the extreme south of England where the winds were very light, the bright areas are associated with valleys, shallow depressions and gaps in ridges.

The conurbation of London itself is virtually clear of bright areas, even though they are present in the estuary of the Thames. As an urban area, its higher surface roughness can increase the depth through which turbulent mixing occurs, preventing or delaying the onset of fog formation. Also, the temperatures in urban areas tend to be higher than in the country, with the same effect.

To the north of London, there is a perceptible flow of air from the south. Bright areas are shown within the small valleys that dissect the Chilterns and their continuation into East Anglia, producing the dendritic pattern in the image. The bright areas cease northward of the ridge in a strip about 50 km wide.

It is plausible to suggest that a combination of a katabatic drainage flow down the sides of individual valleys, coupled with the light general flow from the south, would cause cold air to ascend each valley to the top of the ridge, cooling as it did so. On reaching saturation, fog could form. North of the ridge, the air would descend and warm adiabatically, preventing further condensation. Since some liquid water would be deposited on the upslope, the warming of the air could be enhanced by a *föhn* effect.

The distribution of the bright areas in the north of East Anglia is more problematical, since the lack of significant topography would seem to preclude not only any lifting of moist air, but also any concentration of cold air through katabatic drainage flows. It is possible that local variations in relative humidity are important in such cases.

The Somerset Levels are another area of interest. This region, bounded by hills, is very flat and low-lying with numerous dykes for drainage. It is an area prone to fog and shows up well in Fig. 2.

Other topographical details can be picked out by comparison with a detailed topography map; valleys in the south appear bright, whereas a square-shaped hill in Surrey is dark, surrounded by light areas. In all these examples, the light areas correspond to regions in which fog would be expected to occur.

Clearly shown in Fig. 2 are the dense white areas over South Wales and parts of the Midlands. From their brightness and the presence of billows, it is possible that they are areas of cloud that have formed by the forced ascent of moist air over the hills to the south. Unfortunately, there are no observations to confirm this.

7. Conclusion

It is proposed that there is evidence, both direct and indirect, to support the proposition that the areas of the image in which the brightness temperatures seen in AVHRR channel 4 exceed those in channel 3 by more than one degree are probably the sites of significant banks of water droplets, some of which could be thick enough to reduce the horizontal visibility to less than a few hundred metres.

In the light of the scatter of points in Fig. 3, particularly towards high visibilities, the quantitative aspects of this study should not be emphasized. The case shows some of the complications to be expected in an operational environment. In particular, the fog was thin and patchy, both of which increase the problems of interpretation. However, the qualitative aspects of the image suggest that the technique is potentially of great use to forecasters, since it provides a unique view of the spatial distribution of fog.

Further case studies are being examined in which the fog is thicker and more uniform. It is hoped that these will increase our understanding of the quantitative aspects of the technique. The availability of such images to operational forecasters will provide them with the geographical location of fog at a fixed time but they will still need to use their forecasting skills to predict its development in space and time. The regular use of these images should also increase the understanding of the behaviour of fog, both on synoptic and local scales.

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Gulf Stream variability and European climate

By T.N. Palmer*

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Summary

The influence of mid-latitude oceanic variability on the atmospheric general circulation is not well understood. Nevertheless, some modelling and observational evidence is presented to suggest that, in winter-time, persistent sea surface temperature anomalies near Newfoundland could influence climate downstream over Europe. The discussion is a summary of a more extensive paper which recently appeared in the *Quarterly Journal of the Royal Meteorological Society*.

Introduction

Almost a century and half ago, Sabine (1846) suggested that variations in the strength of the Gulf Stream were 'the cause of remarkably mild winters which occasionally occur in England'. We now know, however, that there is no single cause for such climate variability; indeed, complex models of the atmosphere show considerable inter-annual variability in the absence of any oceanic variability. Despite the enormous advances in our understanding of the atmospheric general circulation since Sabine's time, the role of variations in the position and strength of the Gulf Stream on European climate are not well understood.

One of the regions of the North Atlantic where such variations can be quite marked is to the south-east of Newfoundland, near the interface of the warm Gulf Stream waters and the cold Labrador Current waters. Variation in monthly mean sea surface temperature (SST) in this region can be particularly large (up to 3 K in winter with larger values at other times of the year). Moreover,this is one of the most active regions of the extratropical atmosphere. In winter, with large air–sea temperature differences (associated with cold air streaming off the American continent) and strong meridional SST gradients, cyclogenesis is intense.

Not surprisingly therefore, this region has been the focus of attention of a number of studies investigating the possible influence of mid-latitude oceanic variability on atmospheric climate. Namias (1964), for example, found that blocking activity over northern Europe during the late 1950s was associated with abnormally cold water near the coast of Newfoundland. More generally, Ratcliffe and Murray (1970) found significant lagged correlations between SST in this area (hereafter called the RM area) and surface pressure over Europe, suggesting that a knowledge of SSTs in the RM area may be of importance for long-range forecasting over Europe.

Two important developments have occurred since the work of Namias, and Ratcliffe and Murray, suggesting that further study of the problem is now opportune. Firstly, in the last decade and a half, an enormous amount of effort has been put into the construction of high-quality historical SST data sets suitable for climate studies. The Meteorological Office Historical SST data set (MOHSST) (Minhinick and Folland 1984) is second to none in this respect, careful attention being given, for example, to the correction of biases caused by different methods of measurement. Secondly, there has been substantial development of numerical models of the atmosphere since 1970, and it is now possible to test, in an atmospheric general circulation model (GCM), whether the SST anomalies observed by Ratcliffe and Murray have a consistent influence on the general circulation.

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For these reasons, it was decided to undertake a combined modelling and observational study of the influence of SST in the north-west Atlantic on the general circulation of the atmosphere, using the MOHSST and the Meteorological Office 5-level GCM. This article is an informal synopsis of some of the results of the study which have been published in full by Palmer and Sun (1985).

Model results

The results from eight 50-day winter-time integrations of the 5-level model from four different initial conditions are described first. For each set of initial conditions, two integrations were run: one had the positive SST anomaly, illustrated in Fig. 1(a), added to climatological SSTs, the other had this anomaly subtracted from climatological values. The magnitude of this anomaly is about as large as would ever be observed in the RM area, so the model experiment can be thought of as testing the response to extremes of variation in the north-west Atlantic. Figs 1(b) and 1(c) show the effect of adding or subtracting this anomaly to climatological values. For example, with warm SSTs, the Gulf Stream separates further north from the coast of America and the Labrador Current does not extend as far south.

Fig. 2 shows the 500 mb geopotential height difference field (positive anomaly run minus negative anomaly run) averaged over the four pairs of integrations. For this and other fields, the mean of days

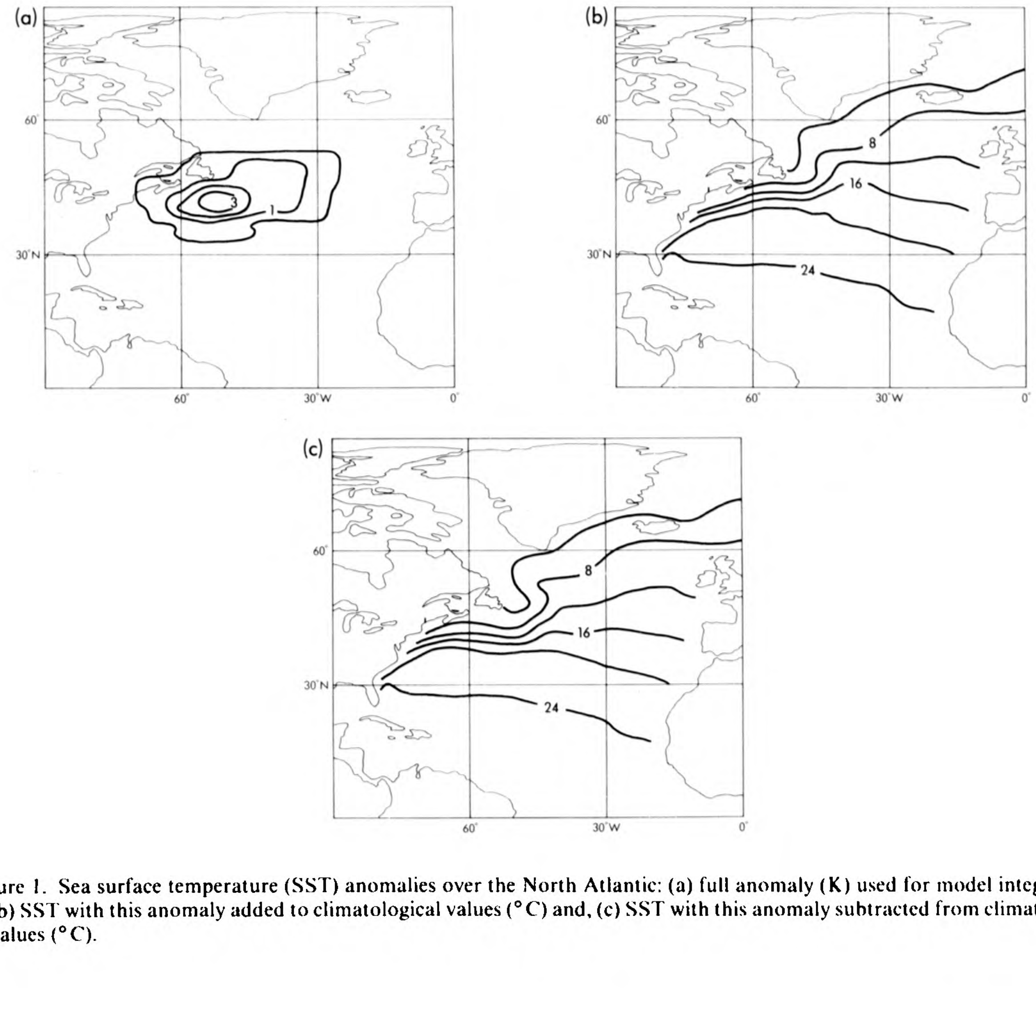

Figure 1. Sea surface temperature (SST) anomalies over the North Atlantic: (a) full anomaly (K) used for model integrations, (b) SST with this anomaly added to climatological values (° C) and, (c) SST with this anomaly subtracted from climatological values (° C).

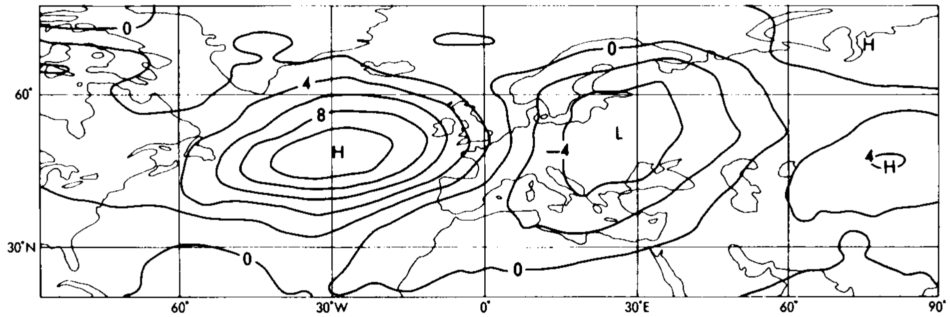

Figure 2. 500 mb geopotential height difference field (dam) averaged over the four pairs of integrations. Each pair consists of one 50-day run with the SST anomaly shown in Fig. 1, and one run with the negative of this anomaly. The mean of days 21–50 is shown.

21–50 of each integration was used. The two main features of this figure are the positive values over the North Atlantic, and the negative values over Europe. Fig. 3 shows this difference for each individual pair of integrations. The main point here is that there are counterparts to the positive and negative values in each of the individual difference fields. Palmer and Sun (1985) showed that the positive and negative values were statistically significant, by performing Student's *t*-tests on the four pairs of integrations. Elsewhere around the hemisphere, the 500 mb height difference field differed substantially from one pair of integrations to the next; from this it must be deduced that there is no consistent response, in such regions, to SST anomalies in the north-west Atlantic.

In order to test whether there is still a discernible signal over Europe and the North Atlantic when the SST anomalies are less extreme, four further pairs of integrations were run with plus and minus half the anomaly shown in Fig. 1(a). The 500 mb geopotential height difference field, averaged over these four pairs of integrations, also showed positive values over the North Atlantic, about half as large as those in Fig. 2, and weak negative values over eastern Europe. However, for this second set of integrations, the difference field varied a lot from one pair of integrations to the next, and results were only of marginal statistical significance.

In trying to understand the dynamical mechanisms at play in these integrations, it was found that the interaction between the mid-latitude cyclones and the time-mean flow was particularly important. It is well known in the theory of the atmospheric general circulation that baroclinic waves play an important part in maintaining the mid-latitude westerlies against frictional dissipation. With warm SST anomalies it was found that the storm tracks over the North Atlantic were displaced north of their normal position; conversely, with cold SST anomalies they were displaced south of their normal position.

A possible explanation for the results in Fig. 2 is that addition of the warm SST anomaly to the climatological value moves the zone of maximum baroclinic instability northward. This in turn moves storm-track activity northward, and thereby intensifies the North Atlantic westerlies. It can be seen from Fig. 2 that north of about 50° N the 500 mb westerlies are enhanced over the Atlantic. These ideas can be made more precise by using the so-called *E*-vector diagnostic (Palmer and Sun 1985).

Observational results

Having obtained the model results, attention was then focussed on the observations by using the MOHSST data as far back as the turn of the century, together with northern hemisphere archived 500 mb geopotential height and surface pressure data. It was also decided to analyse separately the

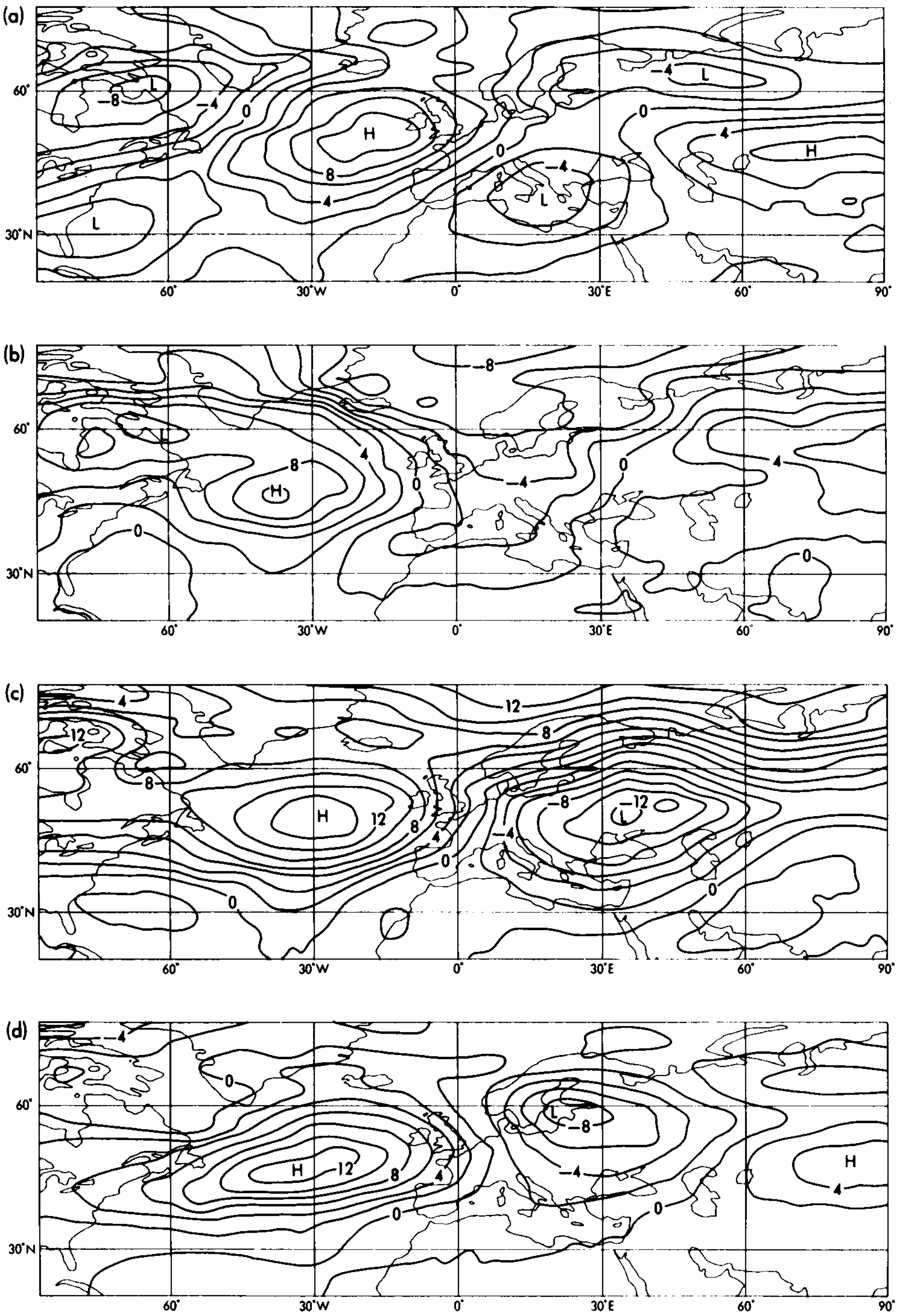

Figure 3. 500 mb geopotential height difference field (dam) for each individual pair of integrations.

periods 1901–30 and 1951–80 to avoid, as much as possible, decadal time-scale trends in the data (Folland *et al.* 1984).

First of all, the RM area was defined to be that within longitudes 60° and 40° W, and latitudes 40° and 50° N. For each month from November to February inclusive, SST anomalies were calculated for 10° × 10° areas over the globe. Cases when monthly mean SST anomalies averaged over the RM area were greater than 0.8 K were grouped together to form a composite warm SST anomaly. Similarly, anomalies in the same area colder than −0.8 K were grouped together to form a composite cold anomaly. The difference between the warm and cold composite SST anomalies is illustrated in Fig. 4 for the 1951–80 data. This clearly illustrates the effect of the compositing, with the difference field having a maximum of 2.4 K in the RM area. Also noticeable is the absence of a significant anomaly in any other area, the tropics in particular.

For each month designated either 'warm' or 'cold', the 500 mb geopotential height and surface pressure anomalies were calculated. These were composited to create mean synchronous atmospheric anomalies associated with the warm and cold composite SST anomalies. The 500 mb geopotential height difference between the composited warm and cold months for the 1951–80 period is illustrated in Fig. 5. Stippling on the figure indicates regions where the difference field is statistically significant (at the 5% level) using Student's *t*-test. A similar composite difference field was calculated using the 1901–30 data which produced very similar results over Europe and the North Atlantic.

Conclusions

The similarities between Figs 2 and 5 are quite striking. Both model and observations show significant positive values over the North Atlantic and negative values over Europe. This similarity suggests that the north-west Atlantic SSTs can indeed have some influence on downstream European climate. There are some differences in detail; for example, the positive centre in Fig. 2 is positioned about ten degrees east of the corresponding observational position. Perhaps the most important 'discrepancy' is the similarity in the magnitude of the model and observational results, given that the model SST anomalies in Fig. 1(a) are about twice as large as the composite SST anomalies in Fig. 4. However, this may not be serious. As diagnosed by Palmer and Sun (1985), the interaction between baroclinic wave activity and the time-mean flow is an important dynamical mechanism in this problem. It would therefore seem reasonable to suppose that a model which is unable to resolve adequately air–sea interaction processes in amplifying cyclones, would underestimate the response to a given SST anomaly in the north-west Atlantic. It is quite possible that the 5-level model, with a horizontal resolution of about 330 km, fits such a description.

The results of this study are in general agreement with the earlier results of Namias (1964) and Ratcliffe and Murray (1970). From Figs 2 and 5, cold SST anomalies in the RM area will tend to be associated with positive geopotential height anomalies over Europe, and hence enhanced ridging and possible blocking. Conversely, warm SST anomalies will tend to be associated with a more progressive westerly type of weather over the British Isles. It has been found that there is significantly more rainfall, particularly over the northern British Isles, when the SST is anomalously warm in the RM area. Of course, these correlations are far from perfect; variability in the north-west Atlantic SST explains only a fraction of monthly-mean climate variance over Europe. Nevertheless, C.K. Folland, of the Synoptic Climatology Branch at the Meteorological Office, has recently found that SST in the RM area is an important winter-time predictor in the multivariate statistical model used for long-range forecasting for the United Kingdom.

One question yet to be asked is what causes the Gulf Stream variability near Newfoundland. The answer is undoubtedly the influence of the atmosphere on the ocean. Palmer and Sun (1985) showed that

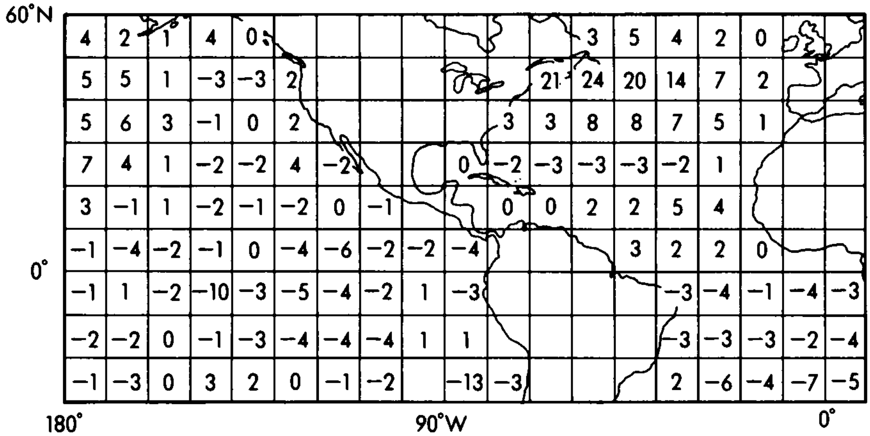

Figure 4. Observed composite sea surface temperature (SST) differences ('warm' — 'cold') in units of 0.1 K using monthly mean SST data averaged over 10° × 10° areas from 1951–80. Blank sea squares indicate missing data.

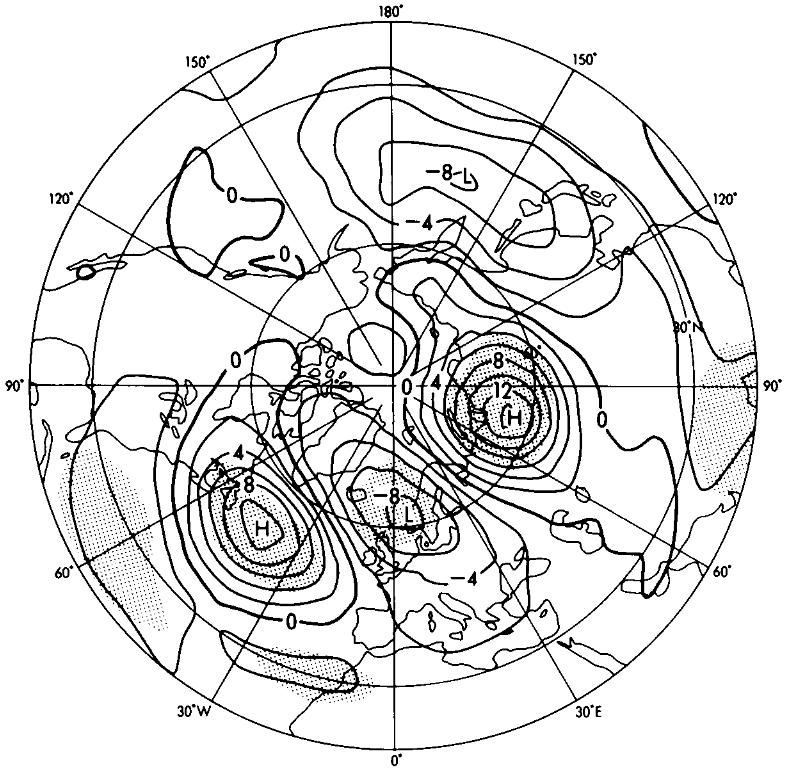

Figure 5. Observed composite 500 mb geopotential height difference field (dam), synchronous with 'warm' and 'cold' months in the RM area (see text), using monthly mean data from 1951–80. Stippling indicates areas that are signficant at the 5% level.

the atmospheric difference field in Fig. 5 had an equivalent barotropic structure (i.e. the patterns have a similar shape at all levels, although different amplitudes), so that the surface wind difference field over the RM area had a marked easterly component. If an anomalous easterly wind stress over the RM area was applied to an ocean model, the surface waters would warm through two effects: a reduction in sensible and latent heat loss from the surface, and the advection of warm waters in the mixed layer by the anomalous Ekman drift current. Such an experiment has been described by Daly (1978).

In summary, therefore, the whole process appears to involve co-operative ocean–atmosphere coupling. Which comes first in setting up the SST anomalies, the ocean or the atmosphere, is really a chicken-and-egg question. We shall never understand the process fully until coupled ocean–atmosphere general circulation models have been developed. Nevertheless, Sabine's conjecture, that Gulf Stream variability can have some effect on British winter-time climate, may have more than a grain of truth in it.

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Conference report

The State of the Art in Numerical Analysis, University of Birmingham, 14–18 April 1986

This conference, organized by the Institute of Mathematics and its Applications and the Society for Industrial and Applied Mathematics, was the third in a series that has been held every ten years to review progress made in the field of numerical analysis. The meeting consisted of 24 review lectures covering all aspects of the subject. Several of the speakers had given similar talks to the previous conference in 1976, and were well placed to review new achievments in the last decade.

The first session was on linear algebra. The problem here is how to handle large matrices such as those arising in statistical regression analysis. It was admitted by at least one of the speakers that in most realistic situations the errors in the data being analysed were much greater than those in the numerical analysis itself, certainly a common situation in meteorology. Also the 32-bit word used on IBM computers is inadequate for many calculations, requiring double precision to be used. A common difficulty in very large (real) problems is the storage of the matrices. Techniques available for data compression using hardware instructions available on such computers as the Cyber 205 were described.

In the second session approximation and data fitting were discussed. These were directly relevant to the analysis problem in numerical forecasting where scattered observations have to be merged with the forecast first-guess field. The theory of data fitting is most developed in one dimension where it is known how to impose monotonicity or convexity on the curve fitting the data points. Multi-dimensional problems are best treated as a product of one-dimensional problems. The best methods also give statistics about the fit achieved for the data. This is very important in the meteorological analysis problem.

The third session was on optimization and non-linear equations. There has been a very large amount of work in this area because of obvious industrial applications. The difficulty here is that a function of a large number of variables has to be minimized, possibly subject to constraints. This involves knowing the derivative of the function with respect to all the variables. These are not usually known analytically and have to be estimated. Evaluations of the function in real problems may be very expensive and it is desirable to do as few of them as possible.

Special problems where the behaviour of the solution can change discontinuously were also described. These represent situations where a mechanical system, for instance, can have more than one equilibrium state but where some of these equilibria become unstable as the control parameters change. It is important to be able to predict such behaviour.

Before the next session there was a talk on 'the sign of zero'. It might be thought that it is irrelevant whether zero is positive or negative, though perhaps not by meteorological observers. There are, in fact, computer calculations where it is important that zero can have a sign because of the limited precision available.

The next session was on ordinary differential equations. In integrating these forward in time it is essential to be able to distinguish correct solutions which grow with time from unstable computational solutions. A great deal of work is being done on finding precise ways to make the distinction, and to determine for which values of the time-step particular integration formulae are stable.

This was followed by a session on integral equations. This is an area where a good deal of progress has been made in the last ten years; partly because of the number of important problems where solutions within a domain have to be deduced from boundary information. The size of such problems can be greatly reduced if they can be formulated in terms of integrals along the boundary rather than over the whole domain. The session was followed by a talk on vector and parallel processors. The Meteorological Office has had a vector processor for some time and a great deal of work went into redesigning the operational analysis and forecast to take advantage of it. Future computers will have several processors which can work in parallel, and algorithms will again need to be redesigned. It is advantageous if the algorithms are insensitive to the order in which the computations are performed, reducing the need for synchronizing the processors.

The final session was on partial differential equations. A great deal of work is going into problems with moving boundaries, such as the oil/water interface in a reservoir. Meteorologists have not yet attempted to apply similar techniques to air masses. New efficient methods have been developed for iterative solution of the finite difference equations arising from steady state problems. Methods for tracking sharp fronts as they cross the domain have been greatly improved, but it is necessary to preserve the sharpness without allowing spurious overshoots. In the Meteorological Office fine-mesh model such overshoots result in spurious rain bands.

Most of the speakers made their material understandable to non-specialists in their particular area. My personal experience is in partial differential equations, so I found the review of work in data analysis very revealing and interesting. This area is as important to the Meteorological Office as are the improved methods for numerical weather and climate prediction. My only complaint was the familiar one of speakers trying to fit their whole talk onto one overhead projector transparency.

The proceeding of the Conference will be published by the Institute of Mathematics and its Applications in due course.

M.J.P. Cullen

Reviews

Handbook of applied meteorology, by David D. Houghton. 160 mm × 230 mm, pp. xv + 1461, *illus.* John Wiley and Sons Ltd, New York, Chichester, Brisbane, Toronto, Singapore. Price £98.25.

The main aim of this book is to provide a comprehensive reference of applied meteorology for professionals and technicians outside the meteorological profession. However, professional meteorologists will find a wealth of material in this massive book, particularly in the areas of applications and measurements. There are 46 chapters by over 50 contributors all, bar one, from the USA, and not surprisingly the subject matter is drawn largely from sources within that country.

The first four chapters in Part I provide a background for the rest of the book by dealing with atmospheric circulation systems, climatology, severe weather and weather forecasting. I suspect the majority of the intended readership will find some of the material difficult to follow, particularly the chapter on weather forecasting which is full of jargon. This chapter contains some interesting outlines of case studies originally published in journals,

Part II has nine chapters on measurements, ranging from ground-based observing systems to satellite-based systems. It gives a comprehensive list of instruments currently in use together with their applications and is a very useful reference work. The largest chapter on satellites is a summary of the history and techniques of satellite meteorology. Unfortunately, the authors miss the opportunity to emphasize the global coverage of satellite-based systems. Meteosat, GMS and INSAT do not rate a mention in this chapter but they are referred to later in the book under the heading of 'data'.

Part III, applications, is the largest section consisting of 25 chapters. The list of applications appears exhaustive and includes water management, agriculture, forestry, air pollution and dispersion measurements, health, architecture, energy, transport, wave propagation and weather modification. As in previous sections the chapter lengths and formats adopted by the authors vary considerably. Acid precipitation merits only 5 pages whereas weather modification fills 75. Forestry (60 pages) deals in some depth with the meteorological influences on forest management. Agriculture (20 pages) has only 2 pages devoted to the use of weather information and forecasts, and would have benefited from the fuller treatment adopted in the forestry chapter and by the inclusion of more information on weather influences on pests. Aviation (32 pages) gives a description of the way weather affects all aspects of flight, but there are no details of forecasting rules. Marine transport and weather-sensitive operations (19 pages) provides information on wave forecasting (including a short program listing) and is aimed chiefly at the offshore industry. Much more could have been written on weather-sensitive marine activities and on the impact of improved weather forecasts, particularly with regard to ship routeing and recreational activities. Energy use is covered by three chapters, one on factors affecting demand (44 pages) and one each on solar energy (25 pages) and wind energy (30 pages). The chapter on weather modification gives a balanced view on the controversial subject of cloud seeding for rainfall enhancement and hail suppression, and also discusses fog clearing and frost protection.

Part IV is a shorter section on societal impacts. The vogue for litigation in the USA has no doubt stimulated the chapter on property rights (although this is inconclusive) and there are chapters on environmental and economic impacts. The latter is only a short chapter and deals only with the impact of variations in climatic elements. There is no attempt to assess the economic benefit of improved forecasts.

The final section of the book, resources, provides an extensive (but not exhaustive) list of data, books and journals (*Meteorological Magazine* is included but not *Tellus* or *Beiträge zur Geophysik*). Research centres, libraries and education centres are also listed. The appendix includes a glossary and a selection of climatic data from around the world.

The professional meteorologist will find this a useful reference book. Most of the chapters on applications are worth reading and may stimulate ideas into finding a wider market for meteorological products. The book is well produced with few errors but the index is poor with many omissions. The page cost compares well with other technical books but at around £100 it is almost a luxury.

T. Davies

Books received

Weather at sea, by D. Houghton (Steyning, Fernhurst Books, 1986. £5.50) is designed as a yachtman's guide to the weather. It clearly explains the basic principles that govern the weather, describes how to use the various weather bulletins and how to draw a weather map from them, shows how to deduce modifications to the wind by the coast or the sea breeze, and how to work out the forecast for a route. It also explains how to keep an eye on developments by watching the clouds, wind, waves and barometer and finishes by discussing hazards such as gales, squalls, thunderstorms and fog.

Floodshock: the drowning of planet earth, by A. Milne (Gloucester, Alan Sutton Publishing Ltd, 1986. £12.95) details the history of the world's great floods from Noah until the present day. The emphasis is put on oceanic and ice-cap factors, including climatic change and catastrophe theory, in explaining the more serious and long-term threat to the world. It is a sequel to Milne's earlier book, *London's drowning*, which suggested that the main threat to London was the growing high surge tide and the sinking of the land. What is happening to London is a salutary warning to the rest of the world.

Air: composition and chemistry, by P. Brimblecombe (Cambridge University Press, 1986. £25.00 (hardback), £8.95 (paperback)) is about the atmosphere and man's influence on it. In the early chapters the author discusses the geochemical, biological and maritime sources of the trace gases; these are followed by chapters on the chemistry of atmospheric gases, suspended particles and rainfall. After dealing with the natural atmosphere the book examines the sources of air pollution and its effects: decline in health, damage to plants and animals, damage to constructional materials, pollution of interiors, acidification of rain, and changes in global carbon dioxide and methane. The final chapters are concerned with the chemistry and pollution of the upper atmosphere and the composition and evolution of the atmospheres of the planets of the solar system.

Meteorological Magazine

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Meteorological Magazine

September 1986

Vol. 115
No. 1370

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ISBN 0 11 727837 8 ISSN 0026–1149

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Printed for HER MAJESTY'S STATIONERY OFFICE
by Delco Printing Co Ltd 9/86 Dd. 739131 C14